Los Alamos
NATIONAL LABORATORY

memorandum

LANSCE Division
Group LANSCE-1

To/MS: Dale Schrage
From/MS: J. Patrick Kelley, MS H817
Phone/FAX: 5-5658/5-2904
Symbol: LANSCE-1:99-080
Date: April 27, 1999
Email: jpk@lanl.gov

SUBJECT: Refrigeration Cost Estimates for a Superconducting High Energy Linac for SNS.

Summary

This document provides estimates for the heat loads for a Superconducting High Energy Linac for SNS, and its distribution system. Using these heat load numbers, the cost for the cryoplant and distribution system (together known as the cryosystem) are estimated, in addition to power, water and liquid nitrogen needs. Two Linac configurations are considered, known as Strawman 1 [1] and Strawman 2 (Attachment 1). Heat loads, cryosystem costs and utility estimates for these accelerators operating at 12% duty factor are provided as Attachment 2 and are partially summarized here.

	Strawman #1	Strawman #2
2 K Heat Load	1,453 W	1,619 W
4.5 – 28 K Heat Load	4,851 W	5,706 W
4.5 K Equivalent Heat Load	6,524 W	7,318 W
Cryoplant Cost (Low Est.)	\$12.1 M	\$13.1 M
Cryoplant Cost (High Est.)	\$15.8 M	\$17.7 M
Distribution System Cost	\$2.25 M	\$2.7 M
Cryosystem Cost (Low Est.)	\$14.4 M	\$15.8 M
Cryosystem Cost (High Est.)	\$18.0 M	\$20.4 M

These costs should be treated as purchased price for a turn-key system. These costs do not include the cost of writing the specification, handling the RFP process, and following the procurement, which will be provided elsewhere. Also not included are the costs of erecting a building, or installing the necessary utilities (water and power) and routing them to the appropriate stub-ups. Attachment 3 provides the impact on cryosystem cost of varying the duty factor. Attachment 4 is a sample spreadsheet of the calculations.

Assumptions

Module Heat Load Calculation Assumptions:

- Each cavity requires only one RF coupler.
- With the exception of cavity heat loads, the heat loads for the APT 0.82 cryomodule [2] are used for the static (MLI, Thermal Intercept, Tuner lever, Supports, Cables, Bayonets and Reliefs, JT, non operating couplers) and dynamic (operating couplers, RF Joints & HOM) load calculations for the

SNS modules. Bayonets, Reliefs and JT loads are not varied with cavity number (module length), while the remainder are scaled to the number of cavities.

- The high beta cavity load is taken to be 84 W, the medium beta cavity load is taken to be 56 W [7].
- No margin is assigned to the cavity RF heat loads, and 40% margin is assigned to all other heat loads.
- A 12% duty factor is assumed which is applied to the cavity and all other dynamic loads.
- The coupler has the same cooling design as the APT coupler: a double point intercept configuration with an inlet temperature of 4.5 K, and an outlet temperature of 28 K. Values for 210 kW of transmitted power are used, adjusted for the duty factor.

Distribution System Heat Load Calculation Assumptions:

- The distribution system consists of a supply and a return transfer line.
- Each transfer line is parallel to, and has the same length as the total length of the High Energy Linac plus an additional 50 m to connect to the Cryoplant. (The Cryoplant will be located 50 m from the Linac).
- The heat load per unit length is assumed to be the same as measured by CEBAF for their transfer lines (0.49 W/m for the 2 K portion of the lines, and 1.91 W/m for the shielding portion of the lines) [3].
- Bayonet boxes and u-tubes are an integral part of the heat load per meter numbers.

Assumptions for Estimating Cryoplant Costs:

- All heat loads are referenced to the equivalent heat load at 4.5 K.
- Refrigerator efficiency at 2 K is assumed to be 0.16 of Carnot. This value is adjusted down from that given in [4] since it is a smaller system than considered in [4] leading to a slight loss in efficiency.
- Refrigerator efficiency at 4.5 K is assumed to be 0.23 of Carnot. This value is adjusted down from that given in [4] since it is a smaller system than considered in [4] leading to a slight loss in efficiency.
- Costs are referenced to the cost of a system purchased by the author for the B&W Cryogenic Test Facility. A description of this system is given in [8]. This 2,700 W @ 4.5 K system was purchased for $5.8 M in 1992 dollars and included cold boxes, compressors, controls, dryers, gas storage, LN storage, spares and some LHe storage [5]. **This is the purchase price and does not include B&W overhead**. Additionally, the vendor's profit margin was minimal.
- Costs are corrected to 1999 dollars using the Marshall & Swift Equipment Cost Index. In 1992, the index was 943.1. In the first quarter of 1999 the index was 1062.7.
- For the low estimate, the Strobridge relationship [6] (cost is proportional to the 0.7 power of refrigeration capacity at 4.5 K) is assumed using the B&W numbers for determining the coefficient.
- For the high estimate, linear scaling of cost vs. refrigeration power is assumed.

Assumptions for Estimating Distribution System Costs:

- The cost per meter number achieved by CEBAF for designing, purchasing materials, building, installing and commissioning their distribution system was used ($3,750/m in 1990 dollars) [9].

- Costs are corrected to 1999 dollars using the Marshall & Swift Equipment Cost Index. In 1990, the index was 915.1. In the first quarter of 1999 the index was 1062.7.

Assumptions for Estimating Utility Consumption and Costs:

- Electric power costs are determined by assuming a cost of $0.05/kW-hr.
- Water requirements were determined by the requirements of a Sullair compressor operating with a 700 HP motor. This unit requires 200 gpm to remove the waste heat of the compression process.
- Nitrogen consumption is estimated using a value of 76.5 L/hr per 1,100 W of refrigeration at 4.5 K. This was a value for the B&W system mentioned previously in the basic Design operating mode [5].
- Nitrogen costs were estimated using a value of $0.07/L, the current cost of LN here at LANL.

The results of the analysis using these assumptions are summarized in Attachment 2 for the 2 Strawmen with a 12% duty factor.

Attachment 3 provides cryosystem costs (refrigerator + distribution system) for the 2 Strawmen as a function of duty factor.

Attachment 4 is a sample spreadsheet of the calculations.

Additional Comments

For an additional reference, a vendor was contacted and asked for a rough estimate for a cryoplant removing 1,000 W @ 2 K, and 4,900 W between 4.5 to 28 K (an equivalent 4.5 K heat load of ~ 4,900 W). These were the numbers obtained for Strawman #1 using scaled APT cavity numbers. Subsequent analysis found the scaling numbers for the cavities to be too low. After 15 minutes of conversation, the vendor felt that the cost of the cryoplant was ~ $10 M, not including the distribution system. Using the assumptions given above, the analysis predicts a low estimate for this size cryoplant of $9.97 M, and a high estimate of $11.9 M.

In comparing the 2 Strawmen, the heat loads and costs for Strawman #2 are higher than for Strawman #1. This is because Strawman #2 has more cavities, couplers, HOMs and RF joints, leading to higher dynamic loads. It also has more cryomodules and the cryomodules are shorter. The bulk of the static heat loads are in the end cap areas of a module. Reducing a cryomodule length has minimum impact on the static heat load. Strawman #2 reduces module length, but increases the number of modules. Therefore the static heat load increases. Finally, the accelerator is longer leading to longer transfer lines and a subsequent increase in heat loads.

References

1. *Strawman Superconducting Linac Design for SNS, Tom Wangler*, Chris Allen, Subrata Nath, Slides presented at the LANL Superconducting Workshop, April 19, 1999.
2. *Preliminary Estimate of APT Cryomodule Heat Loads,* Joe Waynert, ESA-EPE:99-029, Nov. 6, 1998.
3. *SRF History: CEBAF and Cryosystem Heat Loads*, J. Patrick Kelley, LANSCE-1:98-045, February 7, 1998.

4. *Trip report for travel to Thomas Jefferson National Accelerator Laboratory: November 3-4, 1997,* J. Patrick Kelley, LANSCE-1:97-324, December 18, 1997.
5. Supporting documentation is located in the authors files.
6. *An Update on Estimating the Cost of Cryogenic Refrigeration*, R.A. Byrns and M.A. Green, Adv. Cryo. Eng., Vol. 43, Plenum Press, NY 1998.
7. Frank Krawczyk, Private conversations.
8. *B&W's Magnet Test Facility for SSC Collider Quadrupole Magnets*, J.P. Kelley, M.E. Stone, et al., Adv. Cryo. Eng., Vol. 39 A, P. Kittel, ed., Plenum Press, NY 1994, pg. 731.
9. Greg Laughon, Private conversations.

Attachment 1

Strawman Superconducting Linac Parameters

Strawman Superconducting Linac Parameters

	β_G=0.59 section	β_G=0.74 section	Total
Design (geometric) beta	0.59	0.74	
W_{min} (MeV)	167	333	
W_{max} (MeV)	333	1000	
Total energy gain (MeV)	166	666	833
No. cells per cavity	8	8	
Cavity length (m)	0.88	1.10	
Accelerating gradient E_A(MV/m)	9.1	9.7	
Energy gain per cavity (MeV)	6.9	9.3	
RF power per cavity (kW)	250	333	
Estimated aperture radius (cm)	4.75	6	
Estimated E_{peak}/E_A	3.00	2.75	
Estimated average E_{peak} (MV/m)	30	30	
Cavity stored energy (J)	20	24	
Peak Nb wall loss per cavity (W)	33	40	
Q_{ext}	$3.7X10^5$	$4.0X10^5$	
Bandwidth (kHz)	2.2	2.0	
Cavity time constant (μs)	140	160	
Length per period (m)	8.3	13.2	
Length per cryomodule (m)	6.7	11.3	
No. cavities per cryomodule	4	6	
No. cryomodules per klystron	2	1	
No. klystrons	3	12	15
No. cryomodules	6	12	18
No. cavities	24	72	96
Active cavity length (m)	21	79	100
Total cold length (m)	40	136	176
Total length (m)	49.4	158.4	208
Active fraction	0.42	0.50	
Energy gain per meter (MeV/m)	3.4	4.2	4.0
Ave Nb wall loss per section (W)*	55	201	256
Static power load (W)**	80	271	351
Refrigeration load (W)***	203	708	910

* Assume $Q_0=3X10^9$ and 7.2% rf duty factor

** Assume 2W/m of cryomodule for heat leak

*** Assume 1.5 safety factor.

Strawman 2 Superconducting Linac Parameters			
	medium beta section	high beta section	Total
Cavity geometric beta	0.60	0.75	
Wmin(MeV)	200.0	400.0	
Wmax(MeV)	400.0	1000.0	
Total energy gain (MeV)	200.0	600.0	800.0
No. cells per cavity	8	8	
Cavity length (m)	0.90	1.11	
Accelerating gradient EA (MV/m)	8.05	8.66	
Energy gain per cavity (MeV)	6.25	8.33	
RF power per cavity (MW)	0.23	0.30	
Aperture radius (cm)			
Epeak/EA			
Epeak (MV/m)			
Cavity stored energy (J)	22	32	
Peak Nb wall loss per cavity (W)	38	54	
Qext	5.04E+05	5.42E+05	
Bandwidth (kHz)	1596	1484	
Cavity time constant (μs)	199	215	
Lattice period length (m)	5.0	7.6	
Cryomodule length (m)	3.4	5.7	
No. cavities per cryomodule	2	3	
No. cryomodules per klystron	4	2	
No. klystrons	4	12	16
No. cryomodules	16	24	40
No. cavities	32	72	104
Active cavity length (m)	29	80	109
Total cold length (m)	54	136	190
Total length (m)	79	182	261
Active fraction	0.36	0.44	
Energy gain per meter (m)	2.5	3.3	3.1
Ave Nb wall loss per section (W)	87	281	368
Static thermal load (W)	107	272	380
Total refrigeration load (W)	292	830	1122

Attachment 2

Refrigeration Parameters Estimates @ 12 % Duty Factor for Two Strawmen Linacs

Refrigeration Cost Estimates for a Superconducting High Energy Linac for SNS

Strawman #	1	
Medium Beta Module		
# Cavities/Module	4	
# Couplers	4	
Heat Load/Cavity	56	W @ 100% duty
Duty Factor	12	%
Tot. Cavity Heat Load	26.9	W @ 12 % duty factor
2 K Heat Load/Mod.	40.4	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
4.5-28 K Heat Load/Mod.	165.0	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
High Beta Module		
# Cavities/Module	6	
# Couplers	6	
Heat Load/Cavity	84	W @ 100% duty (Q_0 = 3 E 9)
Duty Factor	12	%
Tot. Cavity Heat Load	60.5	W @ 12 % duty factor
2 K Heat Load/Mod.	79.6	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
4.5-28 K Heat Load/Mod.	239.5	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
Accelerator Loads		
# Medium Beta Mod.	6	
# High Beta Mod.	12	
Accel. 2 K Heat Load	1198	W
Accel. 4.5-28 K Heat Load	3864	W
Distribution System		
Length	516	meters
2 K Heat Load	255	W scaled from CEBAF operating experience
4.5-28 K Heat Load	987	W scaled from CEBAF operating experience
Cryosystem Totals		
2 K Heat Load	1453	W
4.5-28 K Heat Load	4851	W
Equivalent 4.5 K Loads	6524	W (4.5 K efficiency 0.23, 2 K efficiency 0.16)
Cost Estimates		
Cryoplant (Low est.)	$12,119,693	Corrected Strobridge curve based on cost of a 2700 W purchased sys.
Cryoplant (High est.)	$15,792,069	Linear scaling of 2700 W purchased sys.
Distribution System	$2,247,104	Based on CEBAF cost/m of transferline installed.
Total (Low)	**$14,366,796**	Sum of Cryoplant Low Est. and Distribution System
Total (High)	**$18,039,173**	Sum of Cryoplant High Est. and Distribution System
Utilities		
Electric (Compressors)	1,926	kW
Electric (Compressors)	$843,465	a year @ $0.05/kW-hr
Water	369	gpm based on 200 gpm/700 HP.
Liquid Nitrogen	454	L/hr based on 76.5 L/hr/1,100 W @ 4.5 K
Liquid Nitrogen	$278,223	a year @ LANL's current price of $0.07/L

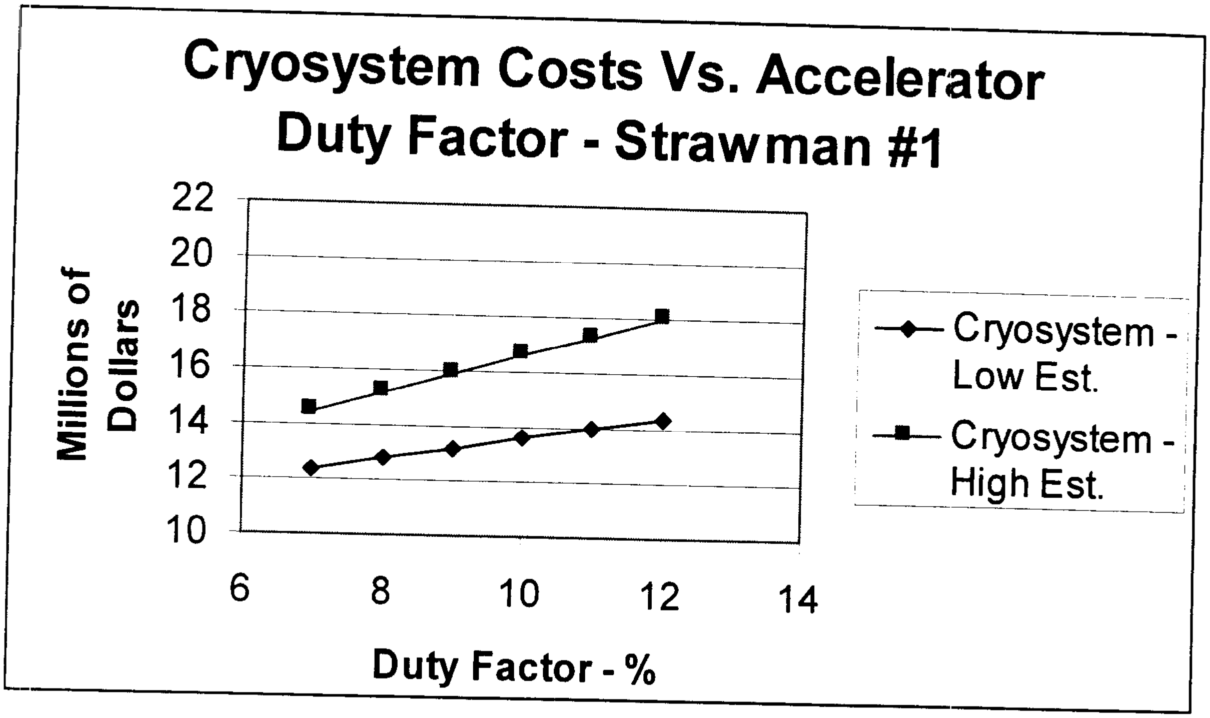
Refrigeration Cost Estimates for a Superconducting High Energy Linac for SNS

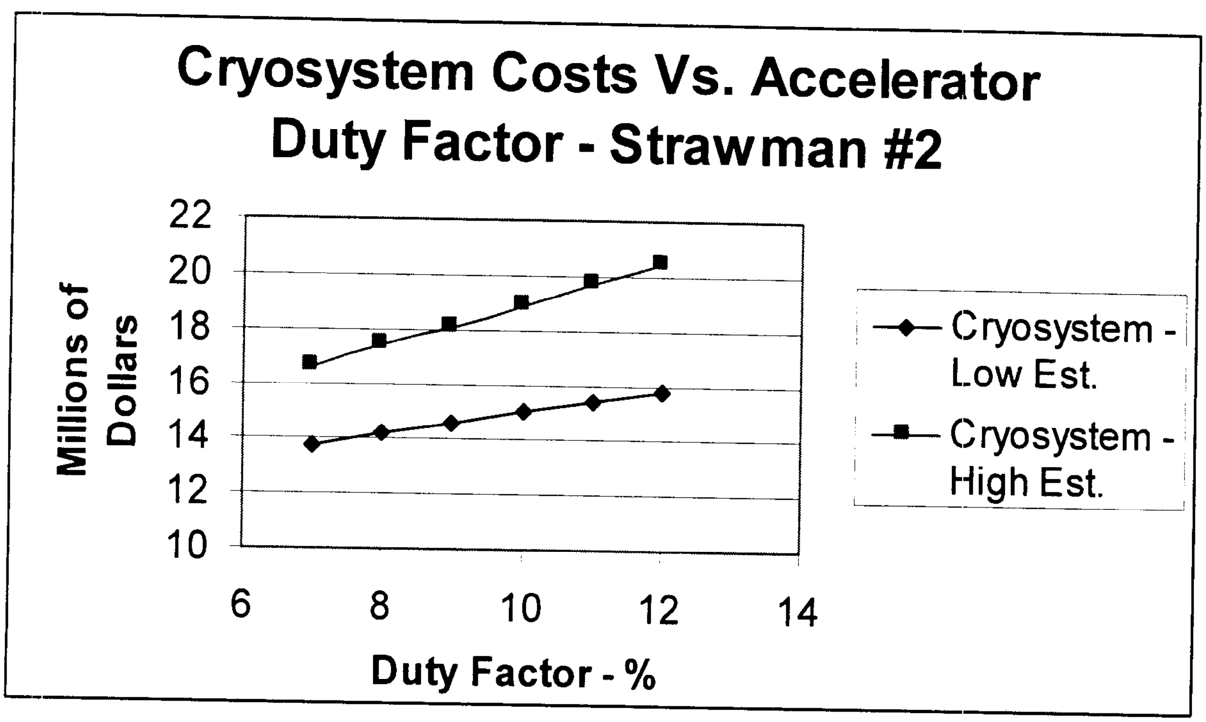
Strawman #	2	
Medium Beta Module		
# Cavities/Module	2	
# Couplers	2	
Heat Load/Cavity	56	W @ 100% duty
Duty Factor	12	%
Tot. Cavity Heat Load	13.4	W @ 12 % duty factor
2 K Heat Load/Mod.	20.6	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
4.5-28 K Heat Load/Mod.	90.6	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
High Beta Module		
# Cavities/Module	3	
# Couplers	3	
Heat Load/Cavity	84	W @ 100% duty (Q_0 = 3 E 9)
Duty Factor	12	%
Tot. Cavity Heat Load	30.2	W @ 12 % duty factor
2 K Heat Load/Mod.	41.0	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
4.5-28 K Heat Load/Mod.	127.8	W static and dyn. loads scaled from an APT 0.82 beta cryomodule
Accelerator Loads		
# Medium Beta Mod.	16	
# High Beta Mod.	24	
Accel. 2 K Heat Load	1312	W
Accel. 4.5-28 K Heat Load	4516	W
Distribution System		
Length	622	meters
2 K Heat Load	307	W scaled from CEBAF operating experience
4.5-28 K Heat Load	1190	W scaled from CEBAF operating experience
Cryosystem Totals		
2 K Heat Load	1619	W
4.5-28 K Heat Load	5706	W
Equivalent 4.5 K Loads	7318	W (4.5 K efficiency 0.23, 2 K efficiency 0.16)
Cost Estimates		
Cryoplant (Low est.)	$13,134,508	Corrected Strobridge curve based on cost of a 2700 W purchased sys.
Cryoplant (High est.)	$17,714,459	Linear scaling of 2700 W purchased sys.
Distribution System	$2,708,718	Based on CEBAF cost/m of transferline installed.
Total (Low)	**$15,843,226**	Sum of Cryoplant Low Est. and Distribution System
Total (High)	**$20,423,177**	Sum of Cryoplant High Est. and Distribution System
Utilities		
Electric (Compressors)	2,160	kW
Electric (Compressors)	$946,141	a year @ $0.05/kW-hr
Water	414	gpm based on 200 gpm/700 HP.
Liquid Nitrogen	509	L/hr based on 76.5 L/hr/1,100 W @ 4.5 K
Liquid Nitrogen	$312,091	a year @ LANL's current price of $0.07/L

Attachment 3

Refrigeration Costs Vs. Duty Factor for Two Strawmen Linacs

The duty factor selected for the Superconducting SNS Linac will be decided by trading off costs for RF control vs. the cost of stiffening cavities to reduce pondermotive oscillations vs. the cost of the cryosystem. The following figures are provided to aid in this evaluation.





Attachment 4

Sample Spreadsheet

Medium Beta SC SNS Cryomodule Heat Loads

Strawman # 2

2 K Heat Loads

Cavity Load @ 100%			Accelerator Length =	*261*	m
Duty Factor	*56*	W	# SNS Cavities/Mod.	*2*	
Duty Factor	*12*	%	# Couplers/Mod.	*2*	
Coupler Static Load	1.64	W ea.	# Modules	*16*	
Coupler Dyn. Load	2.08	W ea. @ 100% duty			
Coupler Dyn. Load	1.69	W ea. @ 12% duty			

				Mimimum Prototype Testing Requirements	Mimimum Production Testing Requirements	Estimated Operational Loads per Module
	0.82 Beta 4 Cavity Module Values (total) - No Margin	100% duty - all cavities running - no margin	12% duty - all cavities running - no margin	12% duty - 100% margin- 2 cavities running simultaneously	12% duty - 0% cavity load margin - 40% margin on all other loads - 2 cavities running simultaneously	12% duty - 0% cavity load margin- 40% margin on all other loads - all cavities running
Cavities		112.00	13.44	26.88	13.44	13.44
Power Couplers		*4.16*	*3.39*	*6.77*	*4.74*	*4.74*
RF Joints	*2.00*	*1.00*	*0.12*	*0.24*	*0.17*	*0.17*
HOM Losses	*6.80*	*3.40*	*0.41*	*0.82*	*0.57*	*0.57*
MLI	*0.20*	*0.10*	*0.10*	*0.20*	*0.14*	*0.14*
Thermal Intercept	0.00	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Tuner lever	0.20	*0.10*	*0.10*	*0.20*	*0.14*	*0.14*
He Vessel Supports	0.08	*0.04*	*0.04*	*0.08*	*0.06*	*0.06*
Cables3	0.80	*0.40*	*0.40*	*5.00*	*0.56*	*0.56*
Bayonets & Reliefs	0.30	*0.30*	*0.30*	*0.60*	*0.42*	*0.42*
JT	0.25	*0.25*	*0.25*	*0.50*	*0.35*	*0.35*
Totals		***121.75***	***18.54***	***41.29***	***20.59***	***20.59***

Medium Beta SC SNS Cryomodule Heat Loads

4.5 to 28 K Heat Loads

Cavity Load @ 100% Duty Factor	0	W	# SNS Cavities/Mod.	2	
Duty Factor	12	%	# Couplers/Mod.	2	

Low Temperature Intercept			*High Temperature Intercept*		
Coupler Static Load	3.36	W ea.	Coupler Static Load	10.1	W ea.
Coupler Dyn. Load	3.66	W ea. @ 100% duty	Coupler Dyn. Load	23.3	W ea. @ 100% duty
Coupler Dyn. Load	3.40	W ea. @ 12% duty	Coupler Dyn. Load	11.7	W ea. @ 12% duty

				Mimimum Prototype Testing Requirements	Mimimum Production Testing Requirements	Estimated Operational Loads per Module
	0.82 Beta 4 Cavity Module Values (total) - No Margin	100% duty - all cavities running - no margin	12% duty - all cavities running - no margin	12% duty - 100% margin- 2 cavities running simultaneously	12% duty - 0% cavity load margin - 40% margin on all other loads - 2 cavities running simultaneously	12% duty - 0% cavity load margin- 40% margin on all other loads - all cavities running
Cavities		0.00	0.00	0.00	0.00	0.00
Power Couplers Low Temp. Intercept		*7.32*	*6.79*	*13.58*	*9.51*	*9.51*
RF Joints	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
HOM Losses	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
MLI	*19.40*	*9.70*	*9.70*	*19.40*	*13.58*	*13.58*
Thermal Intercept	0.90	*0.45*	*0.45*	*0.90*	*0.63*	*0.63*
Tuner lever	5.20	*2.60*	*2.60*	*5.20*	*3.64*	*3.64*
He Vessel Supports	2.00	*1.00*	*1.00*	*2.00*	*1.40*	*1.40*
Cables3	18.50	*9.25*	*9.25*	*50.00*	*12.95*	*12.95*
Bayonets & Reliefs	9.00	*9.00*	*9.00*	*18.00*	*12.60*	*12.60*
JT	2.50	*2.50*	*2.50*	*5.00*	*3.50*	*3.50*
Power Couplers High Temp. Intercept		*46.60*	*23.40*	*46.80*	*32.76*	*32.76*
Totals		***88.42***	***64.69***	***160.88***	***90.57***	***90.57***

Cryomodule Heat Loads

2 K

	Operations			*Test*
	# Modules	**H.L./Mod.** Watts	**Total H.L.** Watts	**High Beta Mod. Total H.L.** Watts
Medium Beta Mod.	16	20.59	329.36	
High Beta Mod.	24	40.95	982.81	58.39
Total			***1312.17***	

4.5 - 28 K

Medium Beta Mod.	16	90.57	1449.10	
High Beta Mod.	24	127.80	3067.28	201.55
Total			***4516.38***	

H_{fg} *@ 2 K =*	23.26	J/g	23.26	J/g
2 K Boiloff =	56.41	g/s	2.51	g/s
$H_{2\,K\ sat.\ gas} - H_{2.6\,K,\ 3\,atm}$ =	18.95	J/g	18.95	J/g
otal flow to modules (with flash) =	69.24	g/s	3.08	g/s
$H_{28\,K} - H_{4.5\,K}$ **@ 18 atm =**	138.59	J/g	138.59	J/g
Coupler/Shield massflow =	32.59	g/s	1.45	g/s

Distribution System Heat Loads

Accelerator Length	261	m	**CEBAF's Tot. Length**	1,300	m
Dist. To Cryoplant	50	m	**CEBAF's 2 K H.L. =**	642	W
Tot. Length (2 Lines)	622	m	**CEBAF'S Shield H.L. =**	2487	W
			CEBAF's 2 K W/m =	0.49	W/m
			CEBAF's Shield W/M =	1.91	W/m

SNS 2 K Loads =	307.17	W @ 2K
SNS Shield Loads =	1189.93	W @ 4.5 - 28 K Circuit
Shield Delta H =	36.51	J/g
Final Shield H =	194.06	J/g
Shield Ret. Temp. =	34.57	K

Dist. System Costs

CEBAF	3750	dollars/m in 1990 dollars
SNS	$ 2,708,718	in 1999 dollars - Corrected with Marshall & Swift Index for 1st qtr 1999 and 1990.

Total Operational Heat Loads

@ 2 K	1619.35	W
4.5 - 28 K Circuit	5706.31	W

Strawman #	2			
Medium Beta Module				
# Cavities/Module	2			
# Couplers	2			
Heat Load/Cavity	56	W @ 100% duty		
Duty Factor	12	%		
Tot. Cavity Heat Load	13.4	W @	12	% duty factor
2 K Heat Load/Mod.	20.6	W static and dyn. loads scaled from an APT 0.82 beta cryomodule		
4.5-28 K Heat Load/Mod.	90.6	W static and dyn. loads scaled from an APT 0.82 beta cryomodule		
High Beta Module				
# Cavities/Module	3			
# Couplers	3			
Heat Load/Cavity	84	W @ 100% duty (Q_0 = 3 E 9)		
Duty Factor	12	%		
Tot. Cavity Heat Load	30.2	W @	12	% duty factor
2 K Heat Load/Mod.	41.0	W static and dyn. loads scaled from an APT 0.82 beta cryomodule		
4.5-28 K Heat Load/Mod.	127.8	W static and dyn. loads scaled from an APT 0.82 beta cryomodule		
Accelerator Loads				
# Medium Beta Mod.	16			
# High Beta Mod.	24			
Accel. 2 K Heat Load	1312	W		
Accel. 4.5-28 K Heat Load	4516	W		
Distribution System				
Length	622	meters		
2 K Heat Load	307	W scaled from CEBAF operating experience		
4.5-28 K Heat Load	1190	W scaled from CEBAF operating experience		
Cryosystem Totals				
2 K Heat Load	1619	W		
4.5-28 K Heat Load	5706	W		
Equivalent 4.5 K Loads	7318	W (4.5 K efficiency 0.23, 2 K efficiency 0.16)		
Cost Estimates				
Cryoplant (Low est.)	$13,134,508	Corrected Strobridge curve based on cost of a 2700 W purchased sys.		
Cryoplant (High est.)	$17,714,459	Linear scaling of 2700 W purchased sys.		
Distribution System	$2,708,718	Based on CEBAF cost/m of transferline installed.		
Total (Low)	**$15,843,226**	Sum of Cryoplant Low Est. and Distribution System		
Total (High)	**$20,423,177**	Sum of Cryoplant High Est. and Distribution System		
Utilities				
Electric (Compressors)	2,160	kW		
Electric (Compressors)	$946,141	a year @ $0.05/kW-hr		
Water	414	gpm based on 200 gpm/700 HP.		
Liquid Nitrogen	509	L/hr based on 76.5 L/hr/1,100 W @ 4.5 K		
Liquid Nitrogen	$312,091	a year @ LANL's current price of $0.07/L		

High Beta SC SNS Cryomodule Heat Loads

2 K Heat Loads

Cavity Load @ 100% Duty Factor	***84***	W	# SNS Cavities/Mod.	*3*
Duty Factor	12	%	# Couplers/Mod.	*3*
Coupler Static Load	1.64	W ea.	# Modules	*24*
Coupler Dyn. Load	2.08	W ea. @ 100% duty		
Coupler Dyn. Load	1.69	W ea. @ 12% duty		

				Mimimum Prototype Testing Requirements	Mimimum Production Testing Requirements	Estimated Operational Loads per Module
	0.82 Beta 4 Cavity Module Values (total) - No Margin	100% duty - all cavities running - no margin	12% duty - all cavities running - no margin	12% duty - 100% margin- 2 cavities running simultaneously	12% duty - 0% cavity load margin - 40% margin on all other loads - 2 cavities running simultaneously	12% duty - 0% cavity load margin- 40% margin on all other loads - all cavities running
Cavities		252.00	30.24	40.32	20.16	30.24
Power Couplers		*6.24*	*5.08*	*10.05*	*7.04*	*7.11*
RF Joints	*2.00*	*1.50*	*0.18*	*0.24*	*0.17*	*0.25*
HOM Losses	*6.80*	*5.10*	*0.61*	*0.82*	*0.57*	*0.86*
MLI	*0.20*	*0.15*	*0.15*	*0.30*	*0.21*	*0.21*
Thermal Intercept	0.00	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
Tuner lever	0.20	*0.20*	*0.20*	*0.40*	*0.28*	*0.28*
He Vessel Supports	0.08	*0.08*	*0.08*	*0.16*	*0.11*	*0.11*
Cables3	0.80	*0.80*	*0.80*	*5.00*	*1.12*	*1.12*
Bayonets & Reliefs	0.30	*0.30*	*0.30*	*0.60*	*0.42*	*0.42*
JT	0.25	*0.25*	*0.25*	*0.50*	*0.35*	*0.35*
Totals		***266.62***	***37.89***	***58.39***	***30.43***	***40.95***

High Beta SC SNS Cryomodule Heat Loads

4.5 to 28 K Heat Loads

Cavity Load @ 100%				
Duty Factor	0	**W**	**# SNS Cavities/Mod.**	3
Duty Factor	12	**%**	**# Couplers/Mod.**	3

Low Temperature Intercept			*High Temperature Intercept*		W ea.
Coupler Static Load	3.36	W ea.	Coupler Static Load	10.1	W ea. @ 100% duty
Coupler Dyn. Load	3.66	W ea. @ 100% duty	Coupler Dyn. Load	23.3	W ea. @ 12% duty
Coupler Dyn. Load	3.40	W ea. @ 12% duty	Coupler Dyn. Load	11.7	

				Mimimum Prototype Testing Requirements	Mimimum Production Testing Requirements	Estimated Operational Loads per Module
	0.82 Beta 4 Cavity Module Values (total) - No Margin	100% duty - all cavities running - no margin	12% duty - all cavities running - no margin	12% duty - 100% margin- 2 cavities running simultaneously	12% duty - 0% cavity load margin - 40% margin on all other loads - 2 cavities running simultaneously	12% duty - 0% cavity load margin- 40% margin on all other loads - all cavities running
Cavities		0.00	0.00	0.00	0.00	0.00
Power Couplers Low Temp. Intercept		*10.98*	*10.19*	*20.30*	*14.21*	*14.26*
RF Joints	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
HOM Losses	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*
MLI	*19.40*	*14.55*	*14.55*	*29.10*	*20.37*	*20.37*
Thermal Intercept	0.90	*0.68*	*0.68*	*1.35*	*0.95*	*0.95*
Tuner lever	5.20	*3.90*	*3.90*	*7.80*	*5.46*	*5.46*
He Vessel Supports	2.00	*1.50*	*1.50*	*3.00*	*2.10*	*2.10*
Cables3	18.50	*13.88*	*13.88*	*50.00*	*19.43*	*19.43*
Bayonets & Reliefs	9.00	*9.00*	*9.00*	*18.00*	*12.60*	*12.60*
JT	2.50	*2.50*	*2.50*	*5.00*	*3.50*	*3.50*
Power Couplers High Temp. Intercept		*69.90*	*35.10*	*67.00*	*46.90*	*49.14*
Totals		***126.88***	***91.29***	***201.55***	***125.51***	***127.80***

Cost

B&W Test Refrigerator	2700	W @ 4.5 K	
B&W Refrig. Cost	5,800,000	dollars ('92)	included tanks, dryers, LN dewar, pumps, LHe dewar, etc. - no facilities
B&W Refrig. Cost	6,535,532	dollars ('98)	Marshall & Swift Equip. Cost Index - 1992-1st qtr 1999
SNS Linear	**17,714,459**	**dollars**	
SNS Strobridge	7,129,528	dollars	cold box and compressors only - Byrnes & Green eq. 1
SNS Strobridge correct	**13,134,508**	**dollars**	

Electric Power consumed	2,160	kW
Electric Power in HP	2,896	HP
Ele. Pwr. Cost/Yr.	946,141	dollars/yr. @ $0.05/kW-hr.
Thermal Prw to H2O	1,080.07	kW @ 50% compressor efficiency between 85 and 105 degrees F
GPM	414	gpm (700 HP Sullair compressor requires 200 gpm between 90 and 105 F)
LN consumption	508.96	L/hr @ 76.5 L/hr per 1,100 W @ 4.5 K (Based on B&W CTF design case).
LN cost/yr	$ 312,091	dollars/yr. @ $0.07/L

Operations Refrig. Equivalent 4.5 K Heat Load for the Double Point Intercept Case

Shield/Coupler

massflow	Tin	Pin	hin	Tout	Pout	delta h	Thot	W310
	K	atm	J/g	K	atm	J/g	K	W
32.59	4.5	18	18.91	5	18	1.49	310	3120.37
32.59	5	18	20.4	6	18	3.44	310	6206.42
32.59	6	18	23.84	7	18	4.12	310	6269.04
32.59	7	18	27.96	8	18	4.91	310	6453.63
32.59	8	18	32.87	9	18	5.74	310	7467.23
32.59	9	18	38.61	10	18	6.46	310	7091.98
32.59	10	18	45.07	11	18	6.88	310	6395.20
32.59	11	18	51.95	12	18	7.02	310	5938.02
32.59	12	18	58.97	13	18	6.98	310	5413.66
32.59	13	18	65.95	14	18	6.85	310	4902.75
32.59	14	18	72.8	15	18	6.7	310	4449.62
32.59	15	18	79.5	16	18	6.55	310	4055.58
32.59	16	18	86.05	17	18	6.42	310	3721.50
32.59	17	18	92.47	18	18	6.29	310	3426.07
32.59	18	18	98.76	19	18	6.24	310	3204.13
32.59	19	18	105	20	18	6	310	2912.87
32.59	20	18	111	21	18	6.1	310	2807.26
32.59	21	18	117.1	22	18	5.9	310	2579.99
32.59	22	18	123	23	18	5.9	310	2456.78
32.59	23	18	128.9	24	18	5.8	310	2304.32
32.59	24	18	134.7	25	18	5.8	310	2202.55
32.59	25	18	140.5	26	18	5.7	310	2072.41
32.59	26	18	146.2	27	18	5.7	310	1987.19
32.59	27	18	151.9	28	18	5.6	310	1874.70
32.59	28	18	157.5	29	18	5.7	310	1834.71
32.59	29	18	163.2	30	18	5.6	310	1735.23
32.59	30	18	168.8	31	18	5.5	310	1642.49
32.59	31	18	174.3	32	18	5.6	310	1613.47
32.59	32	18	179.9	33	18	5.5	310	1530.38
32.59	33	18	185.4	34	18	5.5	310	1479.35
32.59	34	18	190.9	34.6	18	3.017184	310	790.32
32.59	34.57	18	193.92					

W310 Theoretical for Shield/Coupler Flow = 109,939.24 W

W310 @ 23% of Carnot for Shield/Coupler Flow = 477,996.68 W

$Q_{4.5\,K}$ = 1619.40 W

Modules Heat Load	1312.17	W @ 2 K		Ref. T	310	K
Module Boiloff	56.41	g/s		Ref. P	1	atm
hin @ 3 atm, 2.6 K	5.939	J/g		Ref. H	1625	J/g
sin @ 3 atm, 2.6 K	1.991	J/g-K		Ref. S	31.75	J/g-K
hout @ 2 K sat. (0.0309	24.89	J/g				
sout@ 2 K sat.	12.58	J/g-K		hfg =	23.4	J/g
delta h	18.951	J/g				
Total Massflow	69.24	g/s		ein =	526,658	J/g
Transfer Line Losses	307.17	W		eout =	300,682	J/g
Inlet Losses (10% of tota	30.72	W		delta e =	225,976	
Outlet Losses	276.46	W		eboiloff =	203,291	J/g
Refrigerator hi P out h	5.495	J/g		e destroyed by JT =	22,684	J/g
Refrigerator hi P out T	2.353	K	P = 3.1 atm			
Refrigerator hi P out s	1.784	J/g-K	P = 3.1 atm	delta e in Xfer line =	4,413.65	J/g
Refrig hi P out e	531071.69	J/g		delta e out Xfer line =	38,754	J/g
Refrig low P return in h	28.883	J/g				
Refrig low P return in T	2.679	K	P = 0.028 atm	total delta e =	269,143	J/g
Refrig low P return in s	14.398	J/g	P = 0.028 atm			
Refrig low P return in e	261929	J/g				

W310 @ 16% of Carnot for the 2.0 K Heat Loads = 1,682,142 W @ 310 K

$Q_{4.5\,K}$ due to the total 2 K loads = 5698.91 W @ 4.5 K

tal Work at 310 K for Couplers/Shields and 2.0 K Heat Loads = 2,160,139 W @ 310 K

$Q_{4.5\,K}$ = 7318 W @ 4.5 K